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A Comprehensive Review of QAM-Based Codebook Design for Sparse Technique Code Multiple Access

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Abstract

Modern communication network advancement needs continuous research to develop various technologies relating to 5G and beyond. Since 5G is supposed to support many users with fast data transfer, the Multiple Access Scheme is one of the crucial features that has received the most attention from researchers. One major area of interest is the non-orthogonal multiple access (NOMA) scheme. One solution that shows promise in the NOMA scheme is sparse code multiple access (SCMA), which improves wireless communication's multiuser capacity. This review explains the principle of the SCMA encoder and the mother constellation (MC) design. Further, studied different codebook (CB) designs based on QAM and discussed them using various important factors regarding BER, PAPR, and Euclidean distance (d_E). The discussion shows that hypercube QAM is optimal for SCMA compared to others. Finally, the article also presents the opportunities and difficulties associated with SCMA codebook design in multiple criteria.

Keywords: NOMA, OMA, SCMA, BER, PAPR

1. Introduction

The main objective of Multiple Access (MA), a fundamental technique in wireless communication, is to allow numerous users to utilize limited resources at once efficiently. On the other hand, 5G will require a very high quantity of MA, which will require developing an efficient method that can support many users while lowering latency and complexity. By concentrating on these features, any MA strategy must fulfill the following requirements: the ability to manage several users without interfering with each other, the capacity to optimize spectrum efficiency, and the sturdiness to make cell handovers simple [1-3].

Orthogonal MA (OMA) techniques are commonly used in legacy multiuser communication systems. OMA schemes arrange numerous users in an orthogonal manner about specific resources. Previous wireless networks include time division MA (TDMA), frequency division MA (FDMA), code division MA (CDMA), and orthogonal frequency division MA

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(OFDMA). For instance, with TDMA, no two users can concurrently share the same time slot; instead, each user is assigned a unique time slot. The number of users serviced concurrently in any OMA technique is determined by the amount of orthogonal resources [2-4].

The 5G network and communication standards comprise a minimum peak data rate of 10 Gbps, a latency of 1 ms, and a connection density equal to one million devices per km. In the upcoming wireless network generation, NOMA may share all domains, including time, frequency, and space, with multiusers, addressing these difficulties more effectively and better than the conventional OFDM technique [5, 6].

As an alternative to OMA, as illustrated in Fig. 1, NOMA presents an extra dimension by multiplexing within a conventional time-frequency-code domain. To put it another way, NOMA can be considered an "add-on" that could work sufficiently with current MA methods. The fundamental purpose of NOMA is to accommodate numerous users in the same resource block by multiplexing power and/or code domains. NOMA can be broadly categorized into three classes: multiplexing in several domains, power domain NOMA (PD-NOMA), and code domain (CD-NOMA). NOMA allows 5G networks to considerably increase capacity while raising interference and computational complexity at the receiver side. This is because more additional users can be supported while the limited spectrum of resources is completely utilized [7] [8].

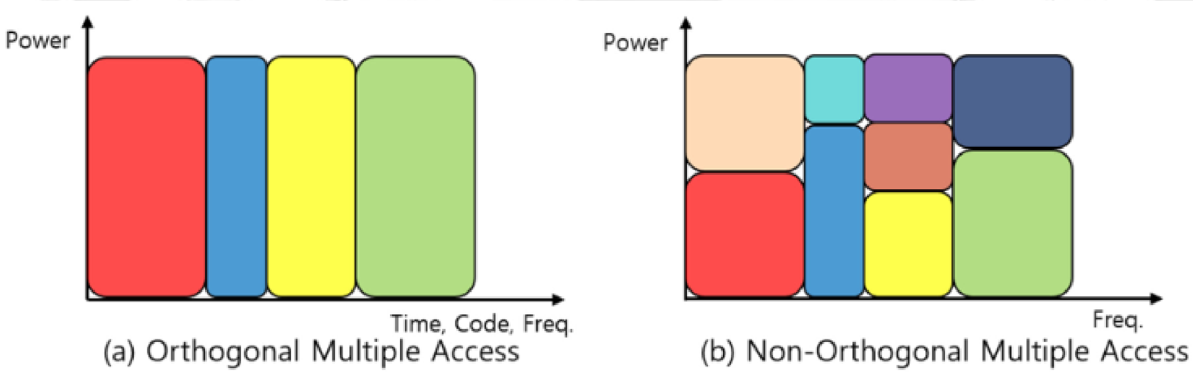

Fig. 1 Schematic OMA and NOMA technique [9]

The new radio (NR) analysis considers several CD-NOMA schemes, including SCMA, one of the most dependable MA options for 5G networks. The SCMA encoder uses a predetermined sparse codebook set to select multidimensional codewords from which the input bits of multiuser streams are directly mapped [10].

The SCMA codebook permits the system to be overloaded with several SCMA layers to facilitate extremely high connectivity. Due to the sparsity of SCMA codewords, near-optimal identification of overlaid SCMA layers is almost possible [11]. The SCMA supports lower complexity and overload [12].

2. SCMA Fundamentals

These subsections explain the highlights of the basic principles of SCMA, including how it can provide MA technique.

2.1 System Model

SCMA's principle is the QAM spread symbol idea, as in CDMA. Thus, direct mapping of bits into sparse codewords is achieved in SCMA by merging the mapping and spreading of the QAM symbol operations [13, 14]. Since every user's CB represents a layer, there will be numerous multidimensional layers as users. The SCMA technique satisfies code sparsity, shaping gain, and coding gain due to the multidimensional modulation of the signals from several users. These features help the receiver since multiplexed low- to moderate-complexity codewords can be decoded using numerous detection techniques [15].

Assume an SCMA approach where J users share K orthogonal resources (RE), and the overload ratio is $\lambda = {}^{J}/_{K}$, $(J > K)$. As illustrated in Fig. 2, the encoder and detector are the primary parts of the SCMA technique. The procedure of the encoder for user J is represented as follows: $f_j: B^{\log_2(M)} \rightarrow \chi_j, \chi_j \subset C^K$, where M is the modulation order. A vector b_j of $\log_2(M)$ represent coded bits for user J is mapped to a K-dimensional codeword x_j chosen from the CB set χ_j. For every complex codeword, x_j, which is a sparse vector, there are (N) nonzero elements and $(N < K)$. Due to the codeword vector sparsity, the number of users that can be superimposed on a single resource is limited, which lowers the computational complexity of multiuser decoding. The received signal can be represented in mathematical form as follows:

$$y = \sum_{j=1}^{j} h_j x_j + n \tag{1}$$

In which $x_j = [x_j^1, x_j^2, \dots x_j^K]^T$ indicates a K -dimensional codeword of user j, $h_j = [h_j^1, h_j^2, \dots h_j^K]^T$ denotes the channel coefficient of user j, and n represents the Additive White Gaussian Noise (AWGN) [16].

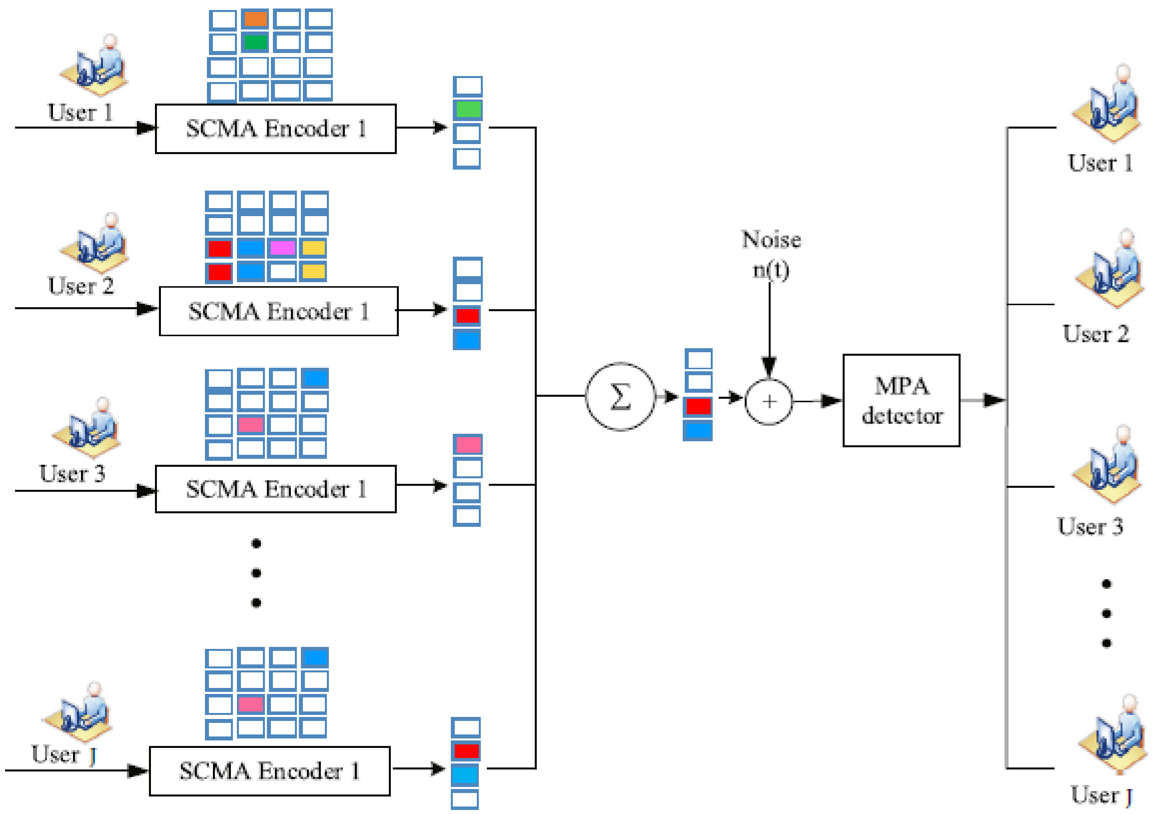

Fig. 2 Transceiver of SCMA system [17]

2.2 SCMA Encoding

Every user has a CB size K×M in SCMA that is specified for them, and each column of this CB is referred to as a codeword. For instance, look at a 4x6 SCMA block encoder with overload factor = $^{6}/_{4}$ = 1.5 , K = 4 and J = 6 users, as illustrated in Fig. 3. As seen in Fig. 4, a factor graph matrix can describe the distribution of REs among users. A row represents a number of RE, and a column represents a number of users. The number of ones in a column is denoted by d_v, and the ones in a row are denoted by d_f. When the J user has active transmission across the k^{th} RE, it is indicated by $F_{kj} = 1$. The factor graph matrix of size 4×6 SCMA, representing Fig. 3, shows resource nodes (RNs) and user nodes (VNs).

$$F_{4\times 6} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \qquad (2)$$

Observe that three users are superimposing over a single RE ($d_f = 3$) and that two nonzero values exist in each column ($d_v = 2$).

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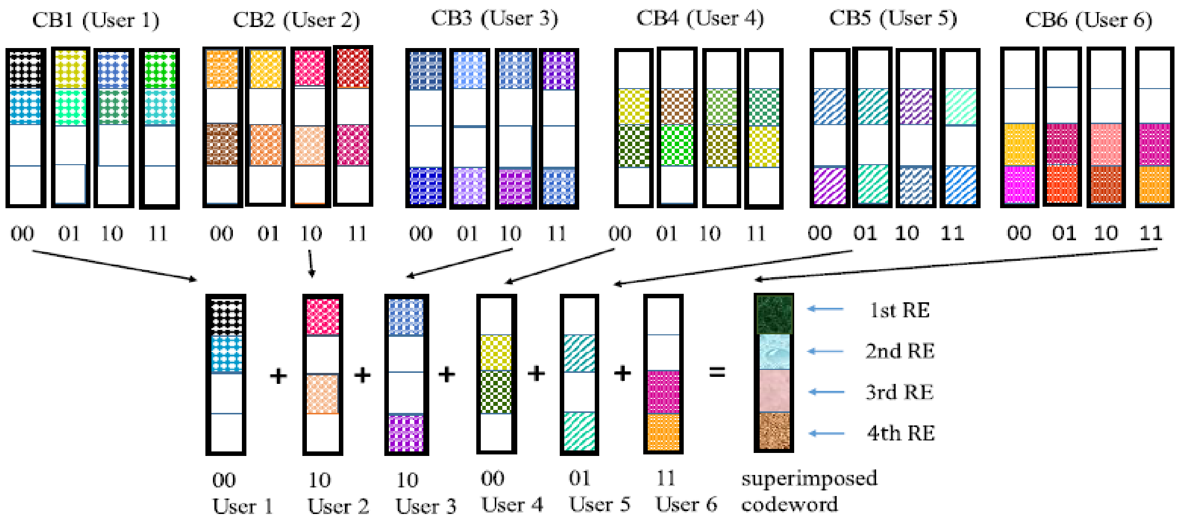

Fig. 3. CB of 4 x 6 SCMA encoder [18]

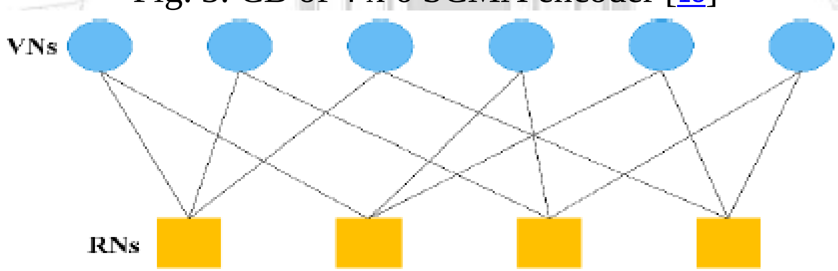

Fig. 4 SCMA factor graph with J = 6 and K = 4 [18]

2.3 SCMA Codebook Design

SCMA outperforms other NOMA techniques better because of its strategically selected sparse CB design. Every user has a unique sparsity pattern in their CB. The SCMA CB design challenge entails determining the ideal multidimensional constellation and mapping matrix, which can be expressed as follows:

$$CB_j = V_j \Delta_j A_{MC} \tag{3}$$

Here, V_j indicates the binary mapping matrix, A_{MC} represents the multidimensional mother constellation (MC) matrix and Δ_j stand to the constellation operator for the j[th] user. According to the mapping matrix selection, users have active transmissions over a few fixed resources. Corresponding to the factor graph matrix, six users' binary mapping matrices are listed below [18]:

$$V_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, V_2 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, V_3 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{4}$$

$$V_4 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, V_5 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, V_6 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Along with determining the complexity of the message-passing algorithm detection, the mapping matrix explains the relationship between the users and the resources. Receiver detection is simple, and the codeword is sparse. However, the factor matrix also allows for the deduction of each layer of the mapping matrix [19]. Common constellation operators include the following three:

Complex conjugate: $$(\circledast:\tau) = \begin{cases} z & \tau = 0 \\ z^* & \tau = 1 \end{cases} \quad (5)$$

Phase operator: $$(\circledcirc:\emptyset)z = e^{i\emptyset}z \quad (6)$$

Vector permutation: $$(\otimes:\pi)z = \pi z \quad (7)$$

In which π is a matrix of permutations. As a result, the operator is stated as [20]:

$$\Delta = (\otimes:\pi)(\circledcirc:\emptyset)(\circledast:\tau) \quad (8)$$

Creating CBs in SCMA involves constructing a multidimensional MC and applying user-specific functions to yield CBs. The MC is designed and tuned to maximize the smallest d_E and attain the largest shaping gain [21]. CB design aims to create and optimize CBs for wireless channels concerning various system evaluation metrics, including bit error rate (BER), and peak-to-average power ratio (PAPR) [22].

3. Mother constellation design based on QAM

3.1 Square QAM

An □ dimensional constellation with □ = □□ points can be created using the cartesian product of QAM. When each codeword energy is constant, the minimal ED of codewords decreases, and the degree of freedom for dimensions is not exploited effectively. The following procedures can be used to construct the MC matrix:

The definition of a subset of lattice Z2 is:

$$S_1 = \{A_m(1+i) | A_m = 2m - 1 - M, m = 1,2, \dots M\} \quad 9)$$

Z is an integer set in this case.

Gray mapping can be used to label every point in subset S1. As an explanation, if □ = 4, the Gray mapping is:

$$\begin{matrix} 00 & 01 & 11 & 01 \\ 3(1+i) & (1+i) & -(1+i) & -3(1+i) \end{matrix} \quad 10)$$

The phase rotation matrix is represented by S□ = U□S1, $U_N = \mathrm{diag}(1e^{i\theta_l - 1}) \in$ C□×□, 1 is □-dimensional all one vector and $\theta_l - 1$ is depicted as:

$$\theta_l - 1 = (l-1) \times \frac{\pi}{MN} \tag{11}$$

Then, a □-dimensional MC based on gray mapping can be formed as [23]

$$A_{MC} = [S_1, S_2, \ldots\ldots S_N]^T \tag{12}$$

3.2 Star QAM

A combination constellation with a large minimum d_E was obtained by design A_{MC} for the SCMA codebook using the Star-QAM constellation as a basis. For instance, take a two-dimensional (N=2) Star QAM of size M = 4 as a SCMA codebook. Then, build a four-ring Star QAM constellation, as illustrated in Fig. 5, where the radii are denoted by $R_1, R_2, \acute{R}_1, \acute{R}_2$, respectively, therefore $\acute{R}_1 = \alpha R_1$, $\acute{R}_2 = \beta R_2$. Thus, the A_{MC}, can be written as [24]:

$$A_{MC} = \begin{bmatrix} \alpha R_1 & R_1 & -R_1 & -\alpha R_1 \\ -R_2 & \alpha R_2 & -\alpha R_2 & R_2 \end{bmatrix} \tag{13}$$

$$|OA| = R_1, |OB| = R_2, |OC| = \acute{R}_1, |OD| = \acute{R}_2 \tag{14}$$

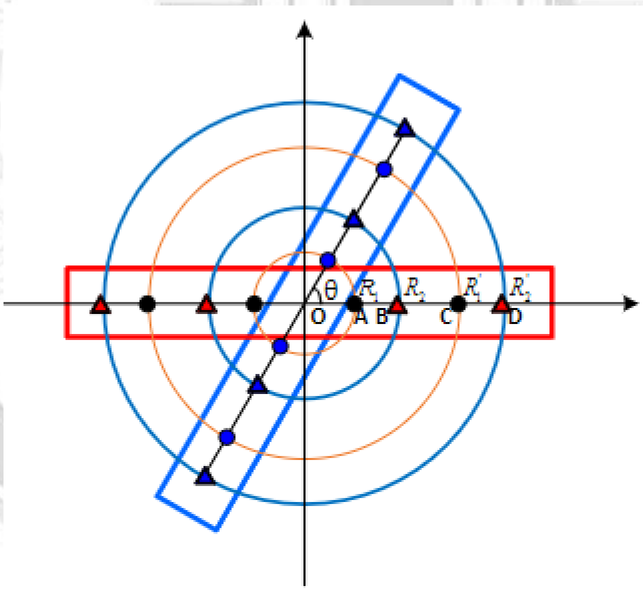

Fig.5 Star QAM constellation design with four rings [24]

3.3 Circular QAM

Circular-QAM's primary goal is to generate MC with fewer projections per tone, decreasing MPA decoding computational complexity while maintaining performance. Defining m as the number of projects for each of the M-point constellation's complex dimensions where m<M. The computational complexity of the MPA decoder will drop to ${d_f}^m$when m is decreased,

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establishing a projection point per tone minimized from M to m reduces the complexity of the constellation size; the circular QAM is represented by (m, M).

For example, the construction of circular-QAM (3,4) is shown in Fig. 6, where N=2 resources of the codebooks are assigned to m = 3 of a 4-point SCMA mother constellation. Two codeword points at the center (origin) and the remaining two codeword points represent the maximum product distance [25].

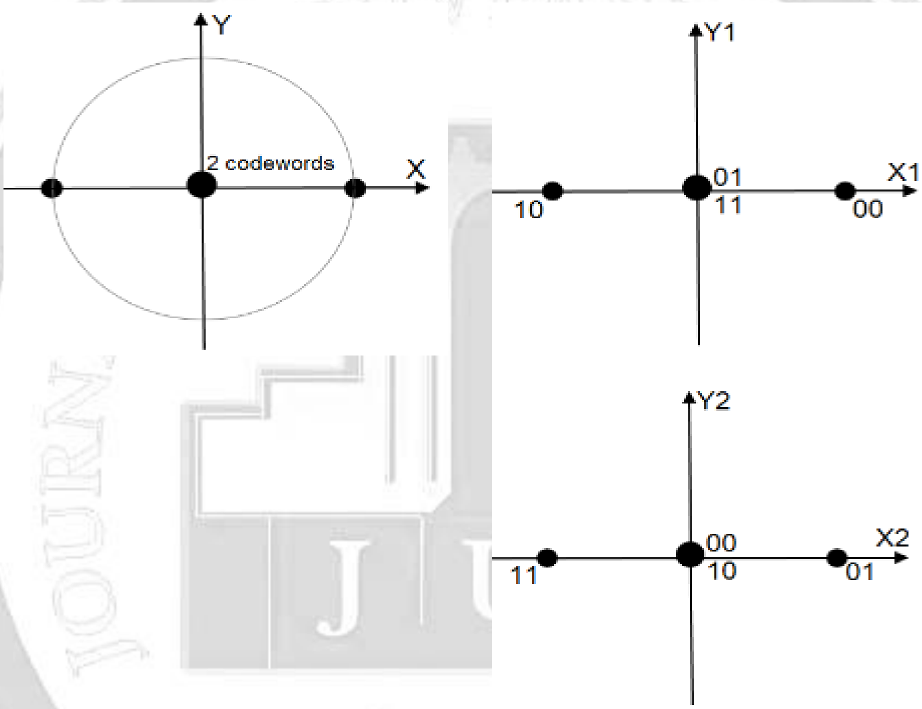

Fig. 6 Circular-QAM (3,4) for SCMA with 4 points and 3 projection points [25]

For a 16-point (M = 16), based on the circular-QAM approach, the projection points can be reduced as shown in Fig. 7. The figure represents the structure of a circular-QAM (9,16) procedure, where the projection points are minimized to 9 by defining 2 rings, each with various ring distances for each tone.

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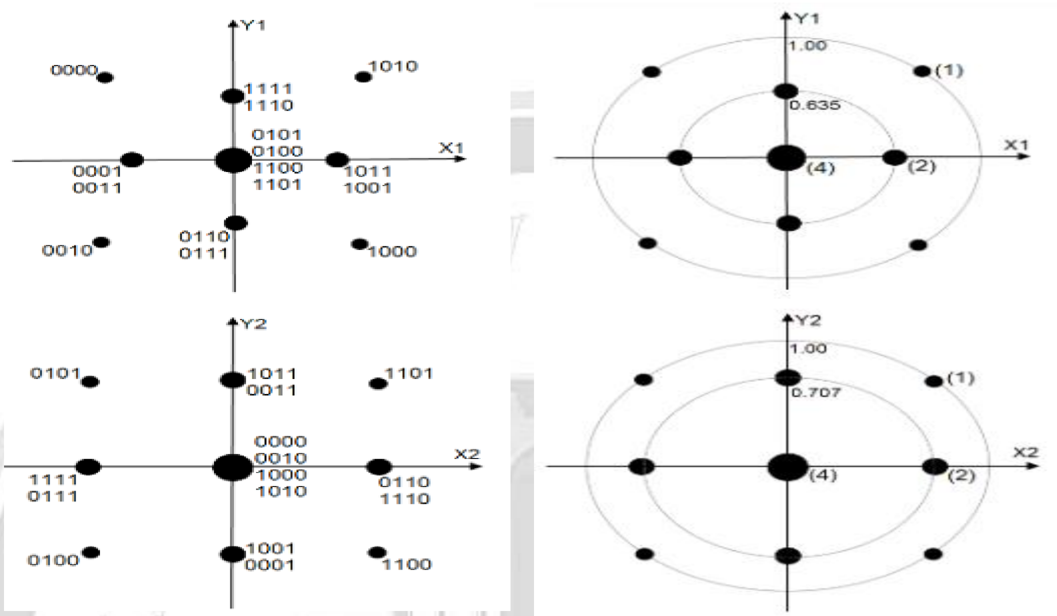

Fig. 7 Circular-QAM (9,16) for SCMA with 16 points and 9 projection points [25]

3.4 Hypercube QAM

Two possible REs, which we named RE_1 and RE_2, are accessible to each user. By taking d_v = 2 and M = 16, the product of two 4-QAM constellations outcomes in points at the 16 corners of a four-dimensional hypercube. As shown in Fig. 8, It is evident that the 16 constellation points are mapped to just 4 points, which may decrease MPA decoding complexity from 16^{d_f} to 4^{d_f}[26, 27].

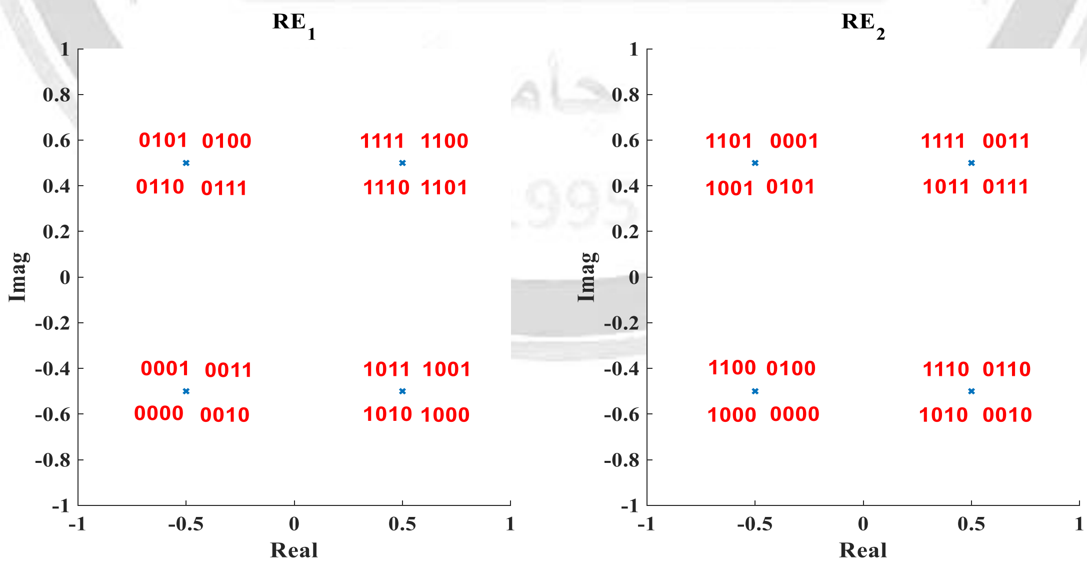

Fig. 8 Four-dimensional, 16-point constellations projected on RE_1 and RE_2[26]

4. key Performance Indicators(KPI) of SCMA Codebook Design

Across many channel environments, the performance of the M-point constellation has a major impact on how well SCMA approaches perform:

A. Euclidian Distance (d_E): The d_E between two constellation points x_m and $x_{\acute{m}}, 1 \leq m < \acute{m} \leq M$ can be calculated as:

$$d_E^{m\acute{m}} = \|x_m - x_{\acute{m}}\| \quad (15)$$

A constellation's minimal d_E is determined as:

$$d_E, min = min\{d_E^{m\acute{m}} | 1 \leq m < \acute{m} \leq M\} \quad (16)$$

B. Euclidian Kissing Number (τ_E)It is the mean number of constellation pairings at the lowest d_E, min.

C. Product Distance (d_p): The d_p between two-dimension complex constellation points, x_m and $x_{\acute{m}}$, is determined as:

$$d_p^{m\acute{m}} = \prod_{j \in \mathcal{J}_{m\acute{m}}} \left| x_{m_j} - x_{\acute{m}_j} \right| \quad (17)$$

In this case, x_{m_j} and $x_{\acute{m}_j}$ are the j^th complex elements of x_m and $x_{\acute{m}}$, respectively. Furthermore, $\mathcal{J}_{m\acute{m}}$ indicates the set of dimensions, j, for which $x_{m_j} \neq x_{\acute{m}_j}$. The minimum d_E is:

$$d_p, min = min\{d_p^{m\acute{m}} | 1 \leq m < \acute{m} \leq M\}$$

18)

Maximizing the d_p, min of the constellation points is known to affect the system's performance in fading conditions significantly.

D. Product Kissing Number (τ_p): It is defined as the mean number of constellation pairs at the d_p, min.

E. Modulation Diversity Order (L): It is defined as the smallest number of unique components that separate any two constellation points for a multidimensional constellation. Otherwise, L represents the smallest Hamming distance between two distinct constellation points. It can be expressed as:

$$L = min\{d_H(x_m, x_{\acute{m}}) | 1 \leq m < \acute{m} \leq M\} \quad (19)$$

Here, the Hamming distance between x_m and $x_{\acute{m}}$ is represented as $d_H(x_m, x_{\acute{m}})$ **[**26**,** 28**].** The KPI of different QAM Constellations used in this paper can be summarized in Table 1 below.

Table .1 Comparison of KPI for various QAM

Constellation Types	d_E	τ_E	d_p	τ_p	L
Square QAM	Moderate	Low	Moderate	Moderate	Low
Circular QAM	Moderate	High	Moderate	Moderate	Low
Hypercube QAM	Low	High	Low	Low	High
Star QAM	Moderate	Low	Moderate	Moderate	Low

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5. Performance Evaluation Metrics of SCMA

The MC matrix design generates an SCMA codebook to reduce the bit error rate (BER). Many methods are proposed to build multidimensional MC for SCMA codebooks to lower PAPR. The codebook with a low number of projections provides a low PAPR. Table 2 shows the effect of QAM type on the SCMA performance.

Table .2 Comparison of QAM in terms of BER and PAPR

QAM Constellation Types	BER	PAPR
Square QAM	Moderate	Moderate
Circular QAM	High	low
Hypercube QAM	low	High
Star QAM	low	High

The primary characteristic of the SCMA approach is its sparse codewords, where the number of sub-carriers determines the length of the codeword, denoted as K. Since each codeword typically has a nonzero element number (N) far lower than K, therefore, is codewords are sparse. The combinatorial number provides a distinct number of codebooks in the following manner:

$$J = C_N^K \tag{20}$$

The nonzero entries in the codeword select the dimension of the SCMA constellation. It is more difficult to generate the codebooks the larger the dimension. Thus, the actual number of N normally should be much less than K/2 to ensure the codewords' sparsity and lower the codebook's dimension.

When increasing the overloading factor λ results in more colliding layers per RE, yet overloading in SCMA allows for a massive connection. Performance depends significantly on the number of colliding layers $d_f = \lambda N$. A RE's BER performance significantly reduces when more codeword elements are superimposed [29].

6. Opportunities and Challenges

The main challenge in codebook design is large-scale codebooks. As the number of users and layers increases, the codebook design problem becomes computationally intensive [30]. An additional essential consideration is power allocation, where balancing power allocation among users ensures fair resource utilization [31]. Furthermore, SCMA codebook design often involves balancing multiple objectives, such as enhancing spectral efficiency, BER, and PAPR. Finding the optimal trade-offs can be challenging [32]. Moreover, SCMA's very high decoding complexity is a significant challenge. Thus, a decoding strategy based on neural networks is needed [33].

7. Conclusion

This survey aims to provide an insightful overview of the current state of codebook design based on QAM for SCMA approaches. The concept of SCMA is explained with its features in addition to the encoder, and mother constellation designs are comprehensively presented. Later, we provided important parameters that affect SCMA performance based on codebook design, such as BER, PAPR, and Euclidean distance. However, the optimal QAM scheme-based CB design choice for the SCMA approach may depend on various factors, such as wireless system requirements and channel conditions. Finally, SCMA performance challenges are explained to find an optimum solution, so the reader is advised to review the original papers and documents further in this survey.

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مراجعة شاملة لتصميم كتاب الشفرات استنادا الى تضمين سعة التربيع لتقنية الوصول المتعدد في الكود المتناثر

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الخلاصة:

إن التقدم شبكات الاتصالات الحديثة يتطلب الاستمرار في تطوير التقنيات المختلفة المتعلقة بشبكات الجيل الخامس وما بعدها. ونظرًا لأن شبكات الجيل الخامس تدعم العديد من المستخدمين في نقل البيانات بسرعة و بنفس الوقت، لذلك فان تقنية الوصول المتعدد تعتبر أحدى أهم الميزات والتي لفتت انتباه معظم الباحثين. ومن أهم هذه التقنيات هي تقنية الوصول المتعدد غير المتعامد (NOMA). ومن افضل التقنيات ضمن NOMA هي الوصول المتعدد بالكود المتناثر(SCMA) ، والتي تعمل على تحسين سعة قناة الاتصال اللاسلكي للعديد من المستخدمين. في هذه المراجعة تم شرح مبدأ SCMA وتصميم كوكبة الأم (MC) . بالاضافة ، تم استعراض التصميمات المختلفة لكتاب الشفرات (CB) وفقا الى تضمين سعة التربيع (QAM) ومناقشها باستخدام عدة عوامل مختلفة ومن اهمها معدل الخطأ في البتات (BER) ونسبة القدرة القصوى الى المتوسطة (PAPR) والمسافة الإقليدية. ومع ذلك، فإن اختيار تصميم كتاب الشفرات الأمثل القائم على تضمين QAM في تقنية SCMA يعتمد على عوامل مختلفة، مثل متطلبات النظام اللاسلكية وظروف القناة. وأخيرًا، تقدم المقالة أيضًا التحديات والفرص المرتبطة بتصميم كتاب الشفرات SCMA في عدة معايير.

الكلمات الدالة:– الوصول غير المتعامد، الوصول المتعامد، الوصول المتعدد للكود المتناثر، معدل الخطأ في البتات، ونسبة القدرة القصوى الى المتوسطة.